Characterizing flow tens of meters from a well

How fluids move through fractured rock formations at distances more than a few meters from a well is largely unknown but important to many fields, including oil and gas production, contaminant transport, and CO_2 sequestration. We propose to demonstrate how tracer and flow testing can characterize fracture flow ~40m from the wellbore in the Horsetooth and Skull Creek members Dakota sandstone where it lies near the surface in Ft Collins, Colorado.

The Dakota produces oil in the nearby Denver Basin where it's porosity is known to be between 7 to 20%. The proposed Ft Collins test site (**Fig. SM1**) has been studied hydrologically because of a spill of contaminated solvents and minor amounts of radionuclides that occurred in the 1950s. It is currently overseen by the Environmental Health Services at Colorado State University who fully support the proposed tests and have offered to assist in obtaining needed permissions, including those for radioactive tracers.

The Dakota at the site has Darcy level, highly anisotropic fracture permeability.   The permeability of 15 intact core samples from 30m deep wells average ~10mD, but injection tests between 24 to 30m depth indicate a permeability of 1 to 10 Darcies. Pressure tests communicate in 100 minutes in the N-S direction but in only 4 minutes in the E-W direction. Br (but not He) was detected 14 hours after the start of injection (4.6 Lpm) in a production well 85 m away produced at 15.6 Lpm (Sanford 2002). Regrettably the test was terminated at 14h due to miscommunication. From nearby outcrops, the fracture spacing is ~0.3m.

Analysis (see **SM.C**) indicates that Sanford's test results are remarkably consistent with what we know about the site, but are surprising in that they require a highly channeled flow. Br arrival in 14h suggests half the flow is within ~5 m from the line connecting the wells, as illustrated in **Figure 1A**. The arrival of Br (with an aqueous diffusion constant D*= 1.02 cm^2 d^{-1}) but not He (with D*= 5.43 cm^2 d^{-1}) is expected from what we know about the site. For a fracture spacing of 0.5 m, Br arrives at detectable concentrations in 14 h, but He remains undetectable for more than a day (**Figure 1B**).

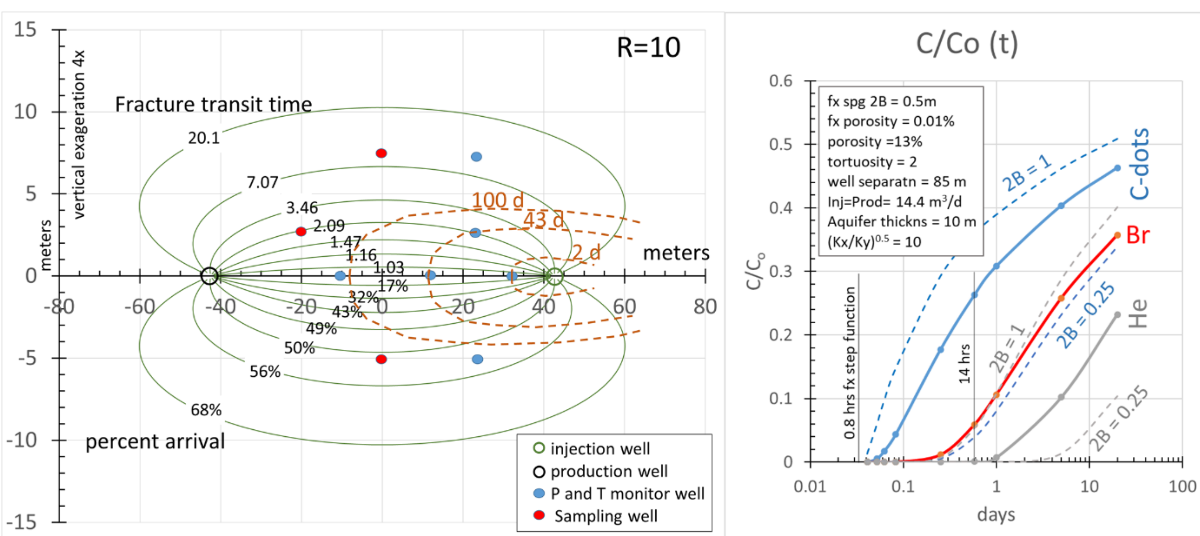


Figure 1.

We propose to redundantly determine the flow characteristics 40m from the well bore at the CSU site by well measurements and tracer testing. In the process, a permanent test site that will be established which will be preferentially available to sponsors.

Eleven, mostly 30m deep wells will be drilled. Their use is shown by color (blue=T-P monitor, red= fluid sampling) in **Figure 1A**. The T-P monitor wells will be instrumented with T-sensing fiber optic cable from 20 to 30m and a pressure gauge at 27m depth. They will be back-filled with low-permeability material. The fluid sampling wells will tap the formation over 0.5 m intervals at 22 27 and 32m depths. The injector and producing wells will be cored from 24 to 36m, backfilled to 30m, cased, and perforated between 24 and 30m.

Table SM1 indicates how the core logging, flow profiling, pressure communication, and tracer tests will constrain the parameters that characterize subsurface fluid flow. Briefly: Pressure testing will indicate flow anisotropy and near-wellbore permeability, and provide a first estimate of fracture spacing, 2B, and minimum fracture aperture, 2b. Inert tracer tests will tightly constrain b and B. Notice, for example that that if the fracture spacing were 1m instead of 0.5m in Figure 2B, He would have been detected at 14h. Notice also how much better the C-dots constrain the minimum fluid transit time between the wells (which constrains B and b). Together, the arrival histories of C-dot, Br, and He will impose very tight constraints on the fracture flow parameters. Hot water is an inert temperature tracer that will propagate slowly the fashion suggested in Figure 1A. The dashed orange lines indicate the thermal front (ΔT = 50% of that injected) after 2, 43, and 100 days of injection. Measurements (blue wells) defining the propagation of the thermal front will indicate the volume through which flow is occurring, confirming the highly anisotropic nature of flow at the site, and indicating the aquifer thickness, H.

The project will begin 1 December (2021 or 2022) and last **1.5 years. December through February** will involve ordering of equipment, refining flow models, and establishing tracer protocols. **March through June**: the wells will be drilling, open hole tested, instrumented, inter-well pressure communication tests conducted, and final plans made. Sponsors will visit the site and critique the plans. **July through August**: The inert and absorbing tracer tests will be conducted and the thermal tracer test initiated. **September through November:** thermal tracer testing continues**. December through June**: Test interpretation, report preparation, presentation of results to sponsors.

Project Budget: The total project cost will be about $1,000,000 including 10% overhead and 10% contingency (33% field and analysis expenses, 66% labor expenses).

Project benefits: Realistic definition of flow away from wells will be defined in an unusually thorough fashion, and a permanent test site established. The most effective ways to constrain distant flow characteristics will be identified.

Supplemental Material

A. The test site

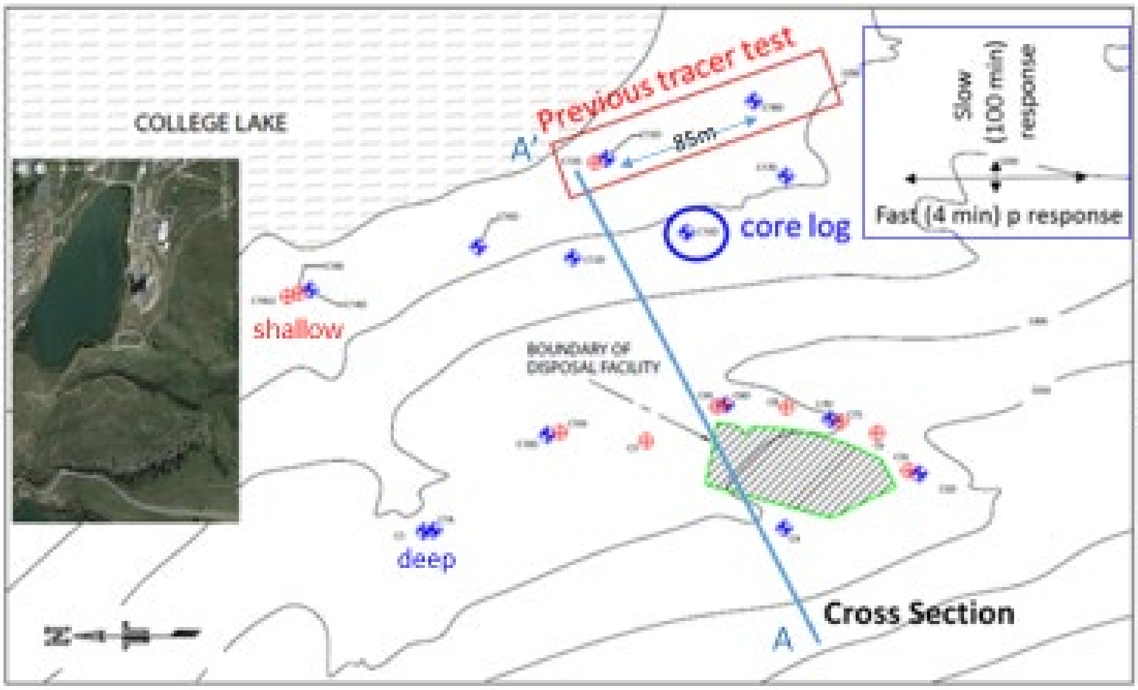


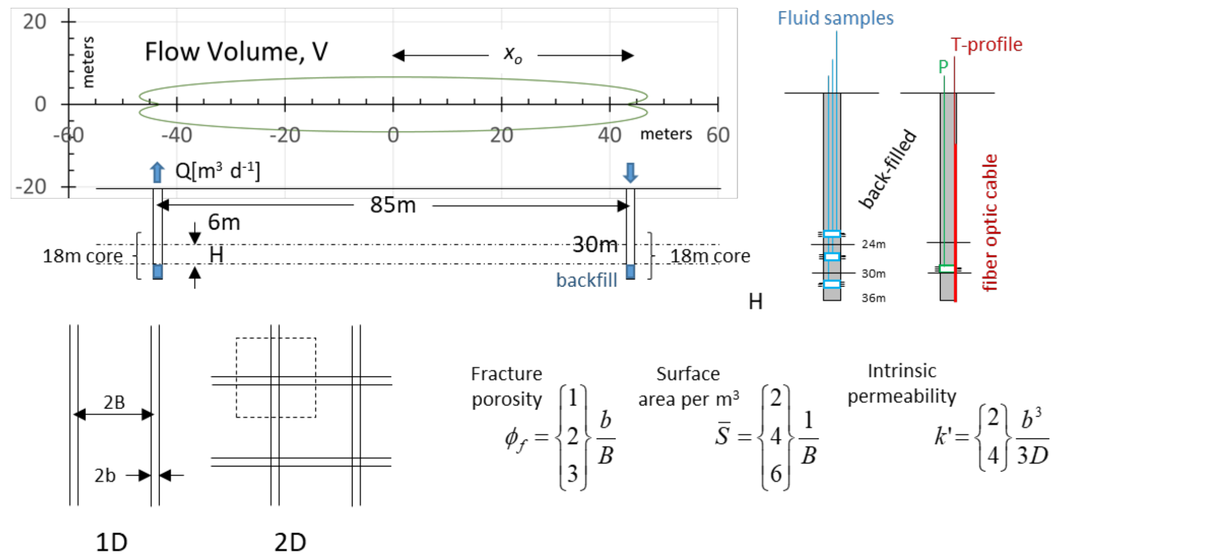
Figure SM1. The Ft Collins test site near College Lake in Ft Collins, Colorado. Existing wells (shallow=red, deep=blue) and location of the Sanford 2002 Br-He tracer test (red box) are shown. A core log is available from the well indicated, but the core is no longer available. Results of a previous tracer communication tests is show in the blue insert.

B. Modeling Methods and how measurements constrain flow characteristics

The Laplace equation for hydraulic head for anisotropic permeability is obtained by transforming the y-coordinate such that $\bar{y} = Ry$, where $R = \sqrt{K_x / K_y}$ and K_x and K_y are the hydraulic conductivities in the x and y directions (e.g., Freeze and Cherry, 1979, p 174). In the anisotropic system, pressure is transmitted R times faster in the x-direction. Pressure testing thus directly suggests flow anisotropy. For dipole flow, streamlines circles with centers on the $\bar{y}$ axis in the transformed $x\bar{y}$ coordinate system, and the transit times along them can be determined as shown in Davis and DeWiest (1966, p207ff). As R increases, the streamlines are increasingly compressed along the x-axis. Figure 1A in the text illustrates the compression for R=10. Flow between the injection and production well is measured by integrating fluid flux in the x-direction up the $\bar{y}$-axis of the from 0 to $\bar{y}$. The flow contribution from various angular outflow sectors of the injector well is determined in this fashion. For R>1, flow across In the anisotropic system the flow across the *y*-axis is compressed by R, the injection head build-up (and production drawdown) is increased by R for the same flow rate, the transit time for all streamlines is decreased by R, and the fracture flow rate along all streamlines is increased by R. In addition, the shortening of the streamlines by the compression reduces the transit time and increases the fracture flow velocities. The efflux from the injector wellbore is modified by the permeability anisotropy, which affects the streamline velocities and transit times. We take this into account. Diffusion from regularly spaced fractures into the matrix, and changes in produced tracer concentration, are calculated from the average fracture flow velocity and the length of each streamline using the dual porosity model of Sudicky and Frind (1982). Tracer contributions of each streamline are summed at the production well. Heat is treated as an inert tracer by taking the matrix porosity as 0.5 and tortuosity equal to 1. This is appropriate because the heat capacity per unit volume of the matrix is approximately half the fluid heat capacity per unit volume, and heat does not diffuse through a tortuous pore path.

The modeling is approximate mainly because the dual porosity model assumes a constant flow rate, whereas the flow rate near the injector and producer wells is much higher than the relatively uniform flow more than ~7m from these wells. When calculating the progression of the thermal front we take this into account by specifying different average fracture flow rates for different distances from the injector. Variable flow rate could be modeled by calculating matrix diffusion by finite element methods at constant travel time locations along the streamline (as in the method of characteristics). The modeling will be refined by doing this in the initial 3-month project period.

Table SM1. Indication how field measurements will constrain flow characteristic variables in 85m between dipole wells. Top figure defines the variables. Middle rows (1-9) indicate constraints. Bottom figure indicates redundancy of parameter constraints by referencing the observation constraint number.



Constraint nbr	description	formula	Constrained variables
1	Well flow profiles, core logs		H
2	Pressure transmission tests		R
3	Dipole pressure drop	$\Delta h = \frac{QR}{2\pi K_x H}\ln\frac{2x_o}{r_w}$	H, b, B
4	Permeability from flow testing	$k' = \begin{Bmatrix}2\\4\end{Bmatrix}\frac{b^3}{B}$	b, B
5$_{(c\text{-}dots)}$, **6**$_{Br}$, **7**$_{He}$	Inert tracer tests	$\frac{C}{C_o} = \frac{Qt}{V\begin{Bmatrix}\phi_f\\ \phi_m\end{Bmatrix}}$	ϕ_m, τ_{tort}, B, b
8	Absorbing tracers	$\alpha\bar{S} = \begin{Bmatrix}2\\4\\6\end{Bmatrix}\frac{V}{B}$	B, V
9	Thermal tracer	$\frac{T}{T_o} = \frac{Qt}{0.5V}$	V, H, R

R	***H***	***V***	***2b***	***2B***	ϕ_m	τ_{tort}
				8		
			7	7		
			6	6		
	9		5	5	7	7
9	3	9	4	4	6	6
2	1	8	3	3	5	5

Left Figure shows histogram of constrained variables.
Notes on constraints:

5,6,7: Brackets indicate range in tracer fill of matrix. As in 9, ratio of delivered tracer to matrix storage volume.

8: Absorbing tracer will arrive when fracture surfaces in flow volume are saturated

1: Logging and flow profiles indicate flowing fxn of H.